

## TIME-OF-FLIGHT SPECTROMETER FOR ULTRA-COLD NEUTRONS

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The production and use of ultra-cold neutrons has been of considerable interest in recent years both because of the possibility of increasing the measurement precision of the intrinsic properties of the neutron itself as well as improving the energy resolution of conventional scattering experiments. We have constructed a rotating-crystal Doppler shifter at the pulsed neutron source at Argonne which shifts neutrons of speed  $\sim 400$  m/s into the ultra-cold range ( $< 10$  m/s), and used this source to develop a high resolution time-of-flight spectrometer. To demonstrate the utility of this spectrometer we present measurements of iron films evaporated on titanium foils. The data reveal the polarization dependence of the transmission as a function of velocity, as well as the quantum-mechanical interference caused by the waves scattered by the iron and titanium. The data collection rates (at ZING-P') are about two orders-of-magnitude higher than achieved at other ultra-cold neutron sources. Energy resolution of  $10^{-7}$ – $10^{-8}$  eV is readily achieved.

### 1. Introduction

The production and use of ultra-cold neutrons has been of considerable interest in recent years both because of the possibility of increasing the measurement precision of the intrinsic properties of the neutron itself, such as the electric dipole moment and the lifetime, as well as improving the energy resolution for conventional scattering experiments [1]. In order to carry out experiments with ultra-cold neutrons, we have constructed [2, 3] a rotating-crystal Doppler shifter at the pulsed neutron source at Argonne National Laboratory, which shifts neutrons of speed  $\sim 400$  m/s into the ultra-cold range ( $< 10$  m/s). We have used this source of ultra-cold neutrons to develop a spectrometer which takes advantage of the pulsed structure of the spallation source to determine the neutron energy by time-of-flight. To demonstrate the utility of the spectrometer we present measurements of the transmission of iron films evaporated on thin titanium substrates. The spin-dependent index of refraction is utilized to

polarize the neutrons, and the observed polarization-dependent transmission is in good agreement with theoretical expectations once the quantum-mechanical interference caused by the waves scattered by the iron and titanium is taken into account. Because the pulsed neutron source is ideally suited for time-of-flight spectroscopy, the data collection rates for the present spectrometer are about two-orders-of-magnitude higher than previously realized at other ultra-cold neutron sources [4, 5]. The primary disadvantage of this spectrometer is the large effective beam divergence ( $\sim 80^\circ$ ) of the incident beam. Collimation can of course be used to restrict the divergence, with a concomitant loss of intensity. There are many experiments, such as thin film transmission and inelastic scattering, where the angular divergence is not important and then the large gain in intensity is a considerable advantage.

### 2. Theoretical considerations

The dominant interactions of neutrons with

matter are the strong nuclear force and the neutron–electron dipolar interaction for materials which possess unpaired electrons (i.e. magnetic materials). For the present interest these interactions may be conveniently written in terms of a potential energy [1, 6]:

$$V^{\pm} = \frac{2\pi\hbar^2}{m} N(a_n \pm p_n), \quad (1)$$

where  $a_n$  is the (s-wave) nuclear scattering amplitude,  $N$  is the atomic density, and  $p_n$  is the magnetic scattering amplitude defined by

$$p = \left( \frac{\gamma e^2}{2mc^2} \right) \mu_z. \quad (2)$$

Here the term in parenthesis is the neutron–electron magnetic dipole coupling constant, and  $\mu_z$  is the  $z$  component of the atomic magnetic moment. The  $\pm$  signs in eq. (1) refer to the relative orientation of the neutron spin and the magnetization. If  $V^+$  and/or  $V^-$  are positive then the interaction for that spin state is repulsive; for neutrons with sufficiently low velocities the potential energy exceeds the component of the kinetic energy perpendicular to the surface and the neutrons are reflected. Quantum mechanically this can be described by the familiar one-dimensional barrier problem, where only the velocity normal to the surface is relevant. For typical materials the critical velocity  $v_c$  at which the potential and (perpendicular) kinetic energies are equal,

$$v_c^{\pm} = (2V^{\pm}/m)^{1/2}, \quad (3)$$

is of the order of a few meters/sec. This velocity corresponds to an equivalent thermal energy of  $\sim 10^{-3}$  K; hence the name ultra-cold neutrons. This is the essential idea for the macroscopic confinement of very low energy neutrons, which for magnetic materials depends on the relative orientation of the neutron spin and the direction of magnetization. We have used this spin dependence to produce a highly polarized beam of ultra-cold neutrons.

An interesting situation arises when the

nuclear and/or magnetic scattering amplitudes in eq. (1) are varied spatially. Such a variation can be achieved, for example, by the deposition of different materials in the form of a thin film. The different materials will correspond to different scattering potentials, which will cause a wavelength dependent interference in the transmitted as well as reflected beams. This effect was first observed for reflected X-rays by Keissig [7], and more recently with neutrons by Spooner et al. [8]. Extension of this procedure to repeated evaporations of two different materials yields a periodic variation of the potential, and this technique has been used to produce artificial “crystals” for use as monochromators of thermal neutrons, including highly polarized beams [9], as well as guides for thermal neutrons [10].

### 3. Results

Fig. 1 shows the experimental setup. Neutrons are reflected from the rotating thermica crystal package to produce a pulse of low velocity neutrons which travel down the Ni guide to the Fe polarizing foils. The effective pulse width at the crystal package is  $\sim 400 \mu\text{s}$  for the present rotor, and the source was operated at 5 Hz for these measurements. Neutrons with energies from 0.1 to  $40 \mu\text{eV}$  were employed in the time-of-flight measurements, which correspond to velocities from 3 to 20 m/s. The first foil effectively polarizes the beam, and the second foil acts as an analyzer. The counts in the detector are analyzed as a function of time.

Fig. 2 shows the data obtained from successive transmission through two  $1600 \text{ \AA}$  Fe films. The data were taken with the foils demagnetized, so that domains in the films were randomly oriented, and with the films magnetically saturated in the same direction. With the films saturated magnetically, the first foil acts as a polarizer, whose efficiency is velocity dependent. There are two critical velocities in this case, one for spin up ( $v_c^+$ ) and one for spin down ( $v_c^-$ ). Note that if the Fe films were very thick (compared to the neutron wavelength) then no neutrons should be transmitted for  $v < v_c^-$ , only one spin state for

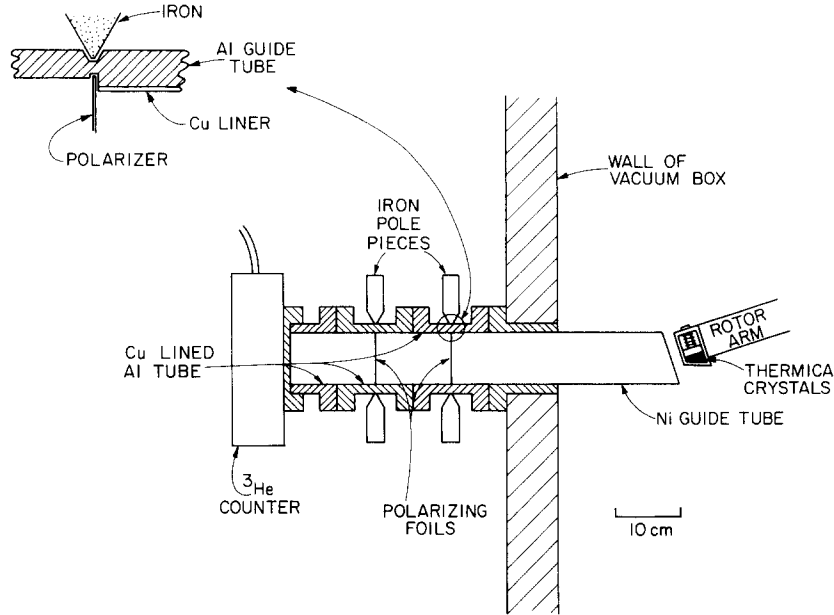


Fig. 1. Schematic diagram of the time-of-flight spectrometer.

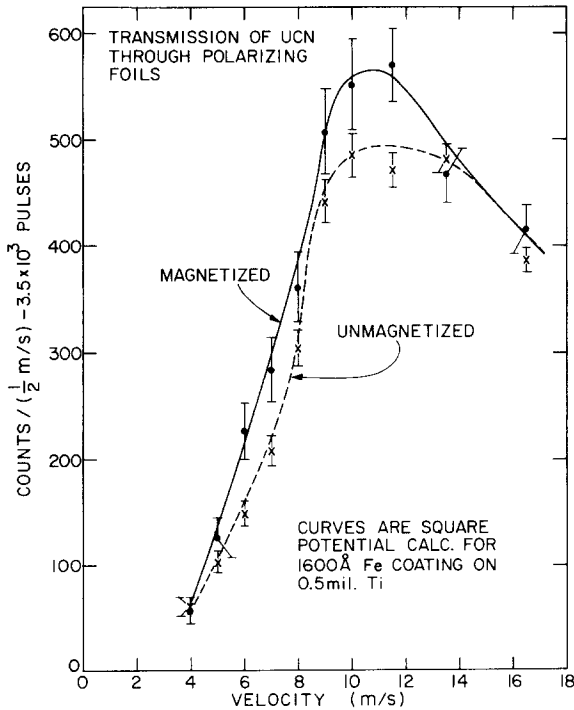
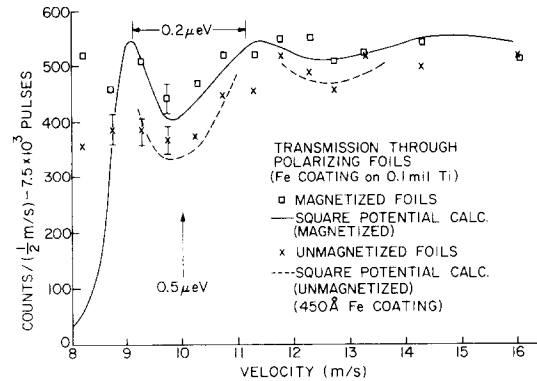


Fig. 2. Transmission of ultra-cold neutrons as a function of velocity through two 1600 Å foils, with the foils unmagnetized (random domain orientations) and with both foils magnetically saturated. These data took a total of 25 min to collect.

$v_c^- < v < v_c^+$ , whereas all neutrons could be transmitted for  $v > v_c^+$ . The second film then has essentially no additional effect on the transmitted beam. For the unmagnetized case the domains are randomly oriented in each film, and thus a neutron transmitted by the first film will likely see a domain with another orientation in the second film. Hence the overall transmission will be reduced in the unmagnetized case, as observed. These data took a total of about 25 min to collect.

The velocity structure of the transmitted beam can be more easily observed with data from

Fig. 3. Transmission as a function of velocity for 450 Å films, showing the interference effects. The spectrometer resolution is  $\sim 4 \times 10^{-8}$  eV.

thinner foils such as that shown in fig. 3 for 450 Å films. The modulation of the transmission agrees reasonably well with the calculations indicated by the curves for both the magnetized and unmagnetized cases. These data can be used to make a rough estimate of the energy resolution of the spectrometer. From the width of the minimum at  $\sim 10$  m/s we can estimate a relative energy resolution of  $\Delta E/E = 8\%$ , which yields an absolute energy resolution of  $4 \times 10^{-8}$  eV. This result is in good agreement with the calculated energy resolution using a numerical simulation.

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